Chapter 2. Overview and Summary

2.1 General Description

The staged approach to the VLHC described in this feasibility study requires placing two collider rings in a common tunnel. This requirement imposes constraints on the lattices of the rings as well as on the civil construction parameters. The injector to the collider is the existing Fermilab accelerator complex, hence the collider must pass through or close to Fermilab.

The plan view of the 233-km VLHC collider is shown in Figure 2.1, which shows the service buildings that contain cryogenic refrigerators and other utilities. Stage 1 has six service areas (one on the Fermilab site) for cryogenics and other operational requirements. Stage 2 requires six additional service sites.

The ring is almost circular, comprising two great arcs of 35-km average radius connected by two clusters, one at Fermilab, one exactly opposite, each six kilometers long and each containing straight sections and dispersion suppressor arcs. The straight sections are needed for various functions necessary for operation, such as injection, extraction, beam cleaning, and the physics detectors.

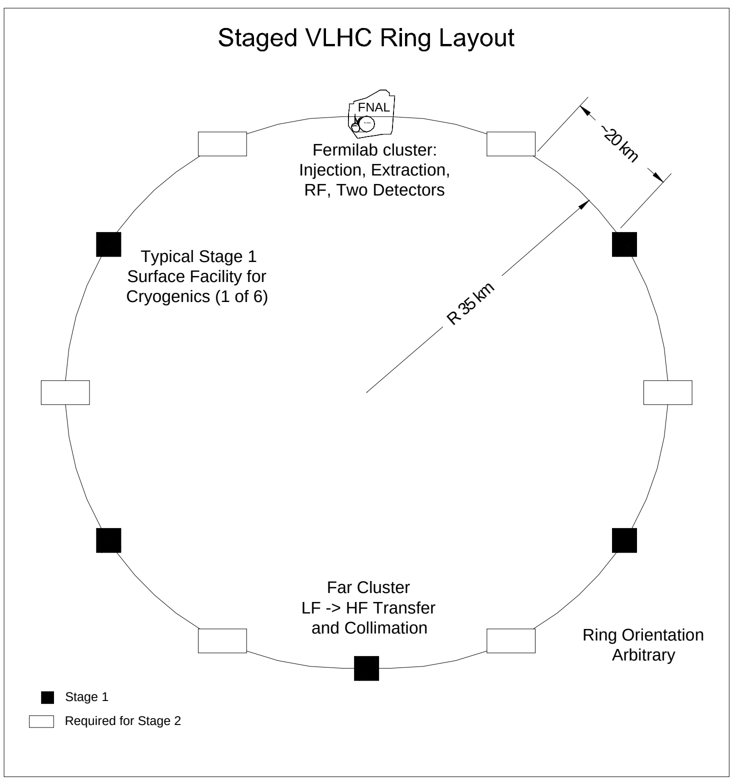

Figure 2.1. The 233-km VLHC ring.

A magnified view of the VLHC Fermilab cluster is shown in Figure 2.2 with one scale extremely expanded relative to the other. Grouped below or nearly below the existing Fermilab site are the underground injection and extraction beam lines, the beam absorber, and the RF acceleration stations. In the on-site straight sections are two detectors, separated sufficiently

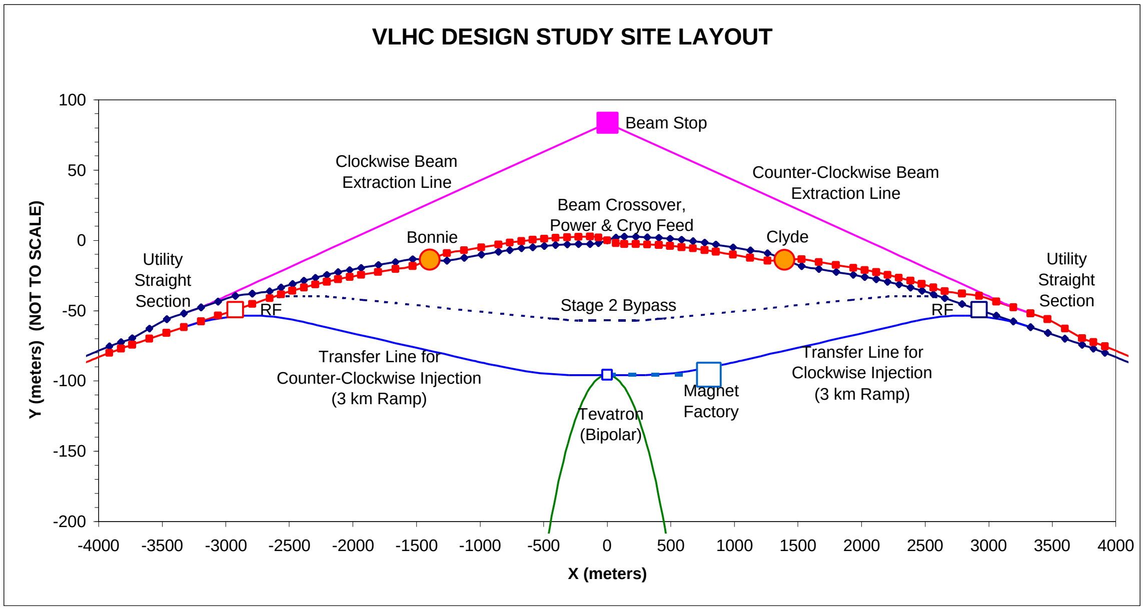

Figure 2.2. VLHC cluster at Fermilab, showing the various functions.
Note the differences in E-W and N-S scales.

in distance and angle to avoid muon background from one detector hitting the other. The cluster opposite the Fermilab site is mostly passive, although a second campus could be developed there. The machine functions at the far cluster are beam cleaning and, eventually, the systems for beam transfer from Stage 1 to Stage 2.

Several different injection layouts from the Tevatron are possible and are discussed in Chapter 4. To take advantage of the best geology in the area, the VLHC tunnel is approximately 120 m below the surface at Fermilab (Figure 2.5), much deeper than the Tevatron, but about the same as the LHC.

The lengths of the injection lines are determined by the desire to descend gradually to that depth so that these ramps can be used during the construction phase for the installation of magnets and other technical components. A similar ramp is used for installation on the far side of the VLHC ring.

The tunnel for this Design Study is a standard tunnel, similar in size to the SSC and LHC tunnels, and made by standard construction techniques. A cross section view of the tunnel at its minimum finished diameter of 12 feet and minimum floor width of 10 feet is shown in Figure 2.3 with the Stage-1 collider installed. Notable are the small Stage-1 combined-function magnet installed on stands on the floor of the tunnel, and the small amount of necessary infrastructure. For example, there is only one small cable tray, because all of the correction elements are powered from local supplies installed in wall penetrations, and all of the instrumentation and controls are local, with only fast communication to the rest of the world. An electric trolley line provides power for tunnel transportation and local work power. This design eliminates almost all long cables except for ring-wide power cables and some bundles of optical fiber.

The Stage-2 collider is shown in Figure 2.4. The Stage-2 magnets are installed vertically above the Stage-1 magnets to preserve the ring circumference. Additional cryogenic service piping, power and cable trays are required.

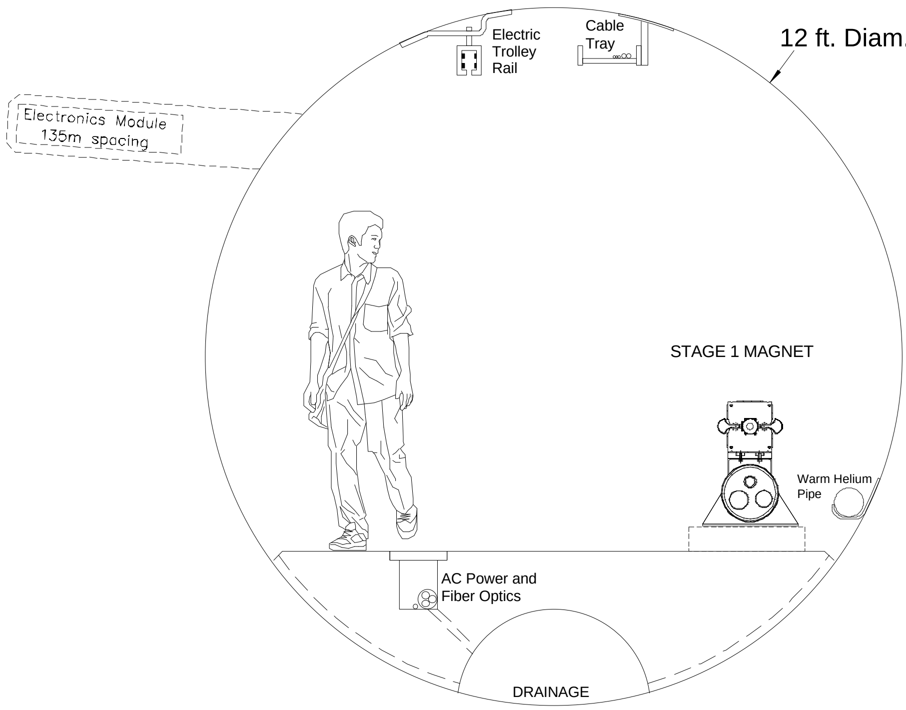

Figure 2.3. A cross section of the VLHC tunnel with the Stage-1 magnets in place.

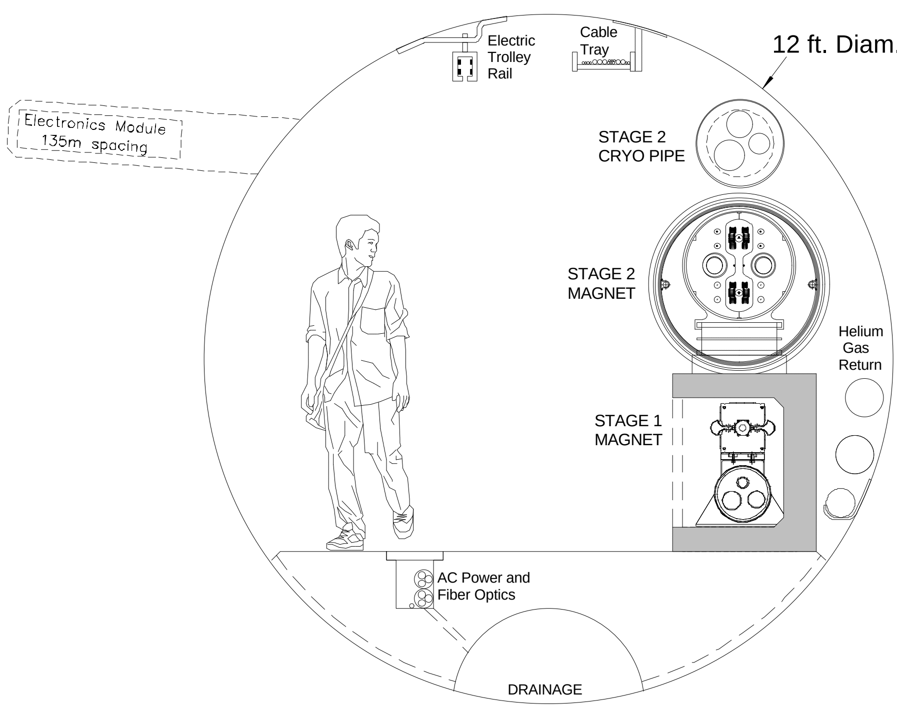

Figure 2.4. A cross section of the VLHC tunnel after the Stage-2 magnets have been installed.

Sections of the tunnel used for services will have to be larger than the nominal minimum of 12 feet. The long straight sections for injection and extraction and experimental areas, the tunnel below the major service buildings, and anywhere where two tunnels join will be among them. In addition, there is an adit to the tunnel every 10 km that contains cryogenic valve boxes and transformers and bulk power supplies for DC power distribution in the tunnel. There are additional personnel exits every 5 km between the 10 km points. Tunnel locations under the service areas and the future locations of the Stage-2 service areas will have adits sized for Stage 2 during the initial construction.

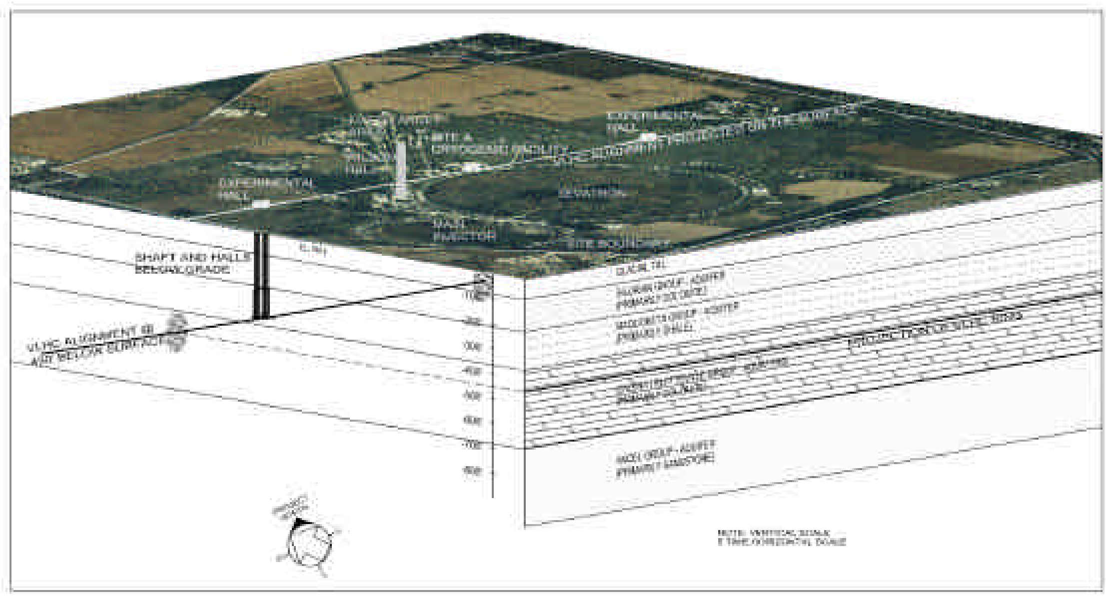

Figure 2.5. A cutaway view of the underground geology at Fermilab with the VLHC tunnel in its approximate location. The vertical scale is expanded relative to the horizontal scales.

2.2 Geology

The terrain in northern Illinois is excellent for building large accelerators. The surface is relatively flat, and there are thick layers of self-supporting and competent rock underground, as can be seen in Figure 2.5. The geology is not perfect, however. The best rock for tunneling, the Galena-Platteville dolomite, is deep underground and is tilted down to the east. There is an inactive fault west and south of Fermilab with a large mismatch of geological properties on either side, and a disturbance from a large meteor strike near Des Plaines. In order to sample all of the features that are in the area, and to get an idea of the technical, environmental and financial issues involved in tunneling through various media, we have included three tunnel orientations discussed in detail in Chapter 7:

- A south ring with a 0.08% incline and a depth at Fermilab of 235 feet. This orientation requires tunneling through the Sandwich fault and is relatively shallow.
- A north ring, with no incline and a depth at Fermilab of 330 feet. This orientation samples numerous types of underground media.

- A north ring with a 0.20% incline and depth at Fermilab of 500 feet. This ring is inclined to stay exclusively in the Galena-Platteville dolomite. It is very deep in some locations.

The tunnel in the dolomite will not be lined but may have to be grouted and sealed in places. Some of the tunnel will have to be lined in order support poorer quality material and to avoid excessive inflow of water, which we have specified as no more than an average of 50 gallons per minute per mile of tunnel. Large underground cisterns are constructed as part of the tunnel near the six major service areas, and pumps with emergency backup empty them. This is a potential environmental issue and the possibility of lining the entire tunnel to reduce the water inflow is being studied.

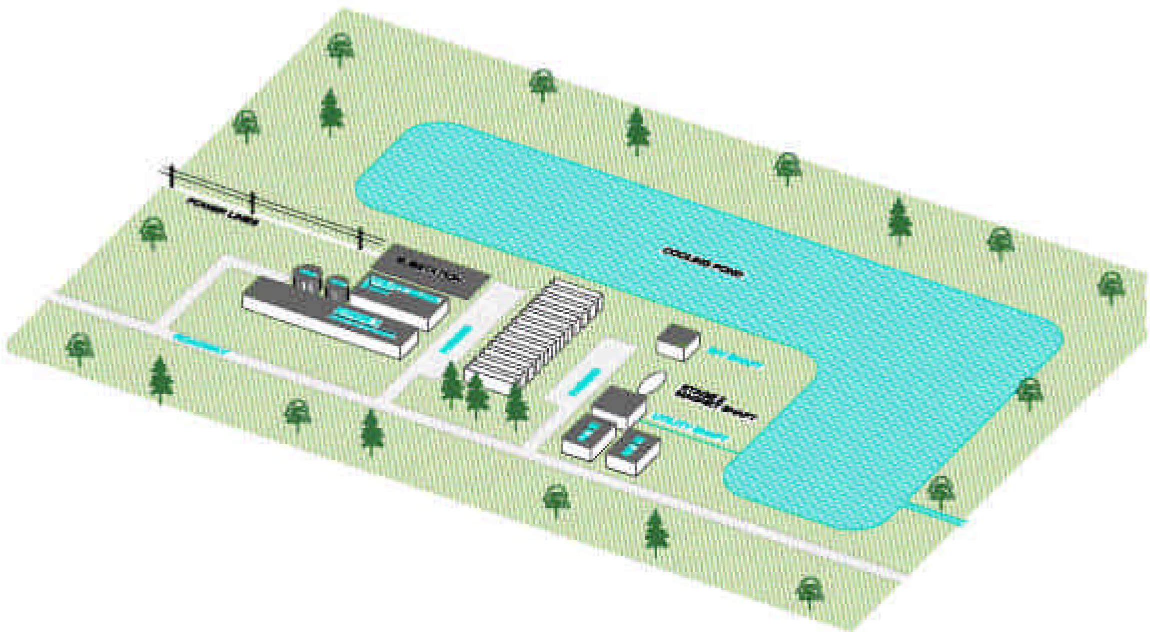

Figure 2.6. A typical service area for the Stage-1 VLHC. The layout of trees, low-profile buildings, and cooling pond provides an aesthetic 10-acre site appealing to the local community.

2.3 Surface Features

The most prominent off-site surface feature of the VLHC will be the service buildings required for refrigeration and other utilities for the collider. Stage 1 needs only six service buildings, roughly 40 km apart. A typical Stage-1 service area is shown in Figure 2.6. One of these is on the Fermilab site and is larger than the others to accommodate additional utilities and cryogenic power required by the experimental areas.

The six Stage-1 service areas are modest, each requiring up to ~10 acres of space, including cooling ponds for 4 MW of installed power. Stage 2 will require six additional sites approximately halfway between the Stage-1 service areas. In this upgrade, all 12 sites will require 40 acres each, with approximately 20 MW of installed power per site. The land use requirements will depend on the mix of cooling ponds versus cooling towers chosen for each service area. Land availability and aesthetics are as important as the technical cost issues in these choices.

The heat rejection capability for Stage-2 compressors is about 8 MW per service area. Minor areas are present at approximately five-kilometer intervals. They will have small buildings to cover and interlock the personnel exits and contain backup (generator) power for the elevators and lights. Every 10 km these buildings will be slightly larger because of additional underground utilities and power requirements.

The two detector caverns and associated service buildings are on the Fermilab site. These caverns are sized according to the SSC design and are 100 m by 30 m by 45 m high. It will be convenient but not necessarily possible to construct them sufficiently deep that their roofs have a thick enough dolomite cover that they will be self-supporting over that large span. The two areas have bending between them so that the background, particularly muons generated in one interaction region will not appear in the other. Experiments similar to those designed for SSC or being built for LHC are thought to be adequate for the 40 TeV collisions of the Stage-1 VLHC.

2.4 The Lattice

While the Stage-2 collider is far in the future, one needs to anticipate its requirements as best one can before laying out the components of the first machine, since they ultimately must reside in same tunnel. This entails anticipating the geometric, space and beam optics requirements for future technical equipment – much of which may not yet be known. This creates the need for conservatism and some compromises. For example, while the size of the arcs is determined by the energy and bend fields of both colliders, the lengths of the straight sections and the interaction regions are determined by the high energy (magnetic rigidity) of the Stage-2 beam. Another complication of the geometry comes about at the transition regions between bending and non-bending portions of the accelerators. Special optical modules – dispersion suppressors – are used to bring the orbits of off-momentum particles to coincide with each other in the long straight sections. Since the Stage-1 and Stage-2 designs have different focusing characteristics, the dispersion suppressors must be designed simultaneously to ensure that the Stage-1 and Stage-2 orbits line up appropriately when entering the long straight sections for the interaction regions and utility regions.

To allow for lattice and component designs to progress simultaneously for both the Stage-1 and Stage-2 colliders, a general layout composed of basic modules was developed. Each collider is made up of two major arcs that connect two clusters of straight sections. The clusters contain space for two nearby interaction regions and two utility regions that are used for injection and extraction, accelerating cavities, and other necessary functions. Short bending regions are located between each interaction region and utility region to allow collision debris and muon vectors to miss the downstream detector and utility enclosures. At the outset, only one cluster region – the one located at the Fermilab site – will be equipped with full interaction region and utility region optics. The other cluster region will have the same straight section lengths, but optically will consist of simple FODO-type modules, with the exception of one area with large dispersion used for beam collimation. Since the Stage-1 magnet has side-by-side apertures, each cluster contains one insertion in which the beams are crossed without colliding, to guarantee equal path lengths for the two beams. The exact length of the standard cell is determined by the chosen bunch spacing. To ensure that bunches will collide at any detector in the design, regardless of what modules exist between interaction points, the ring module lengths are designed in units of the bunch spacing. Details of both colliders are shown in Table 1.1 and 1.2, and in Chapter 3.

2.5 Stage-1 Technical Components

2.5.1 Magnets

The major technical component of the VLHC is, of course, the main arc magnet. The Stage-1 magnet, shown in perspective in Figure 2.7, is a superferric gradient magnet of simple and elegant design. It is not only less costly per Tesla-meter than the typical high-field superconducting magnet, but also requires much simpler and less costly services, such as cryogenics, power supplies, quench protection, and so forth. Since it is a gradient magnet, quadrupoles are not required in the arcs. Its long length, 65 m, presents some challenges in handling and transportation, but reduces the number that need to be fabricated and tested and greatly decreases the overall cost of production and installation.

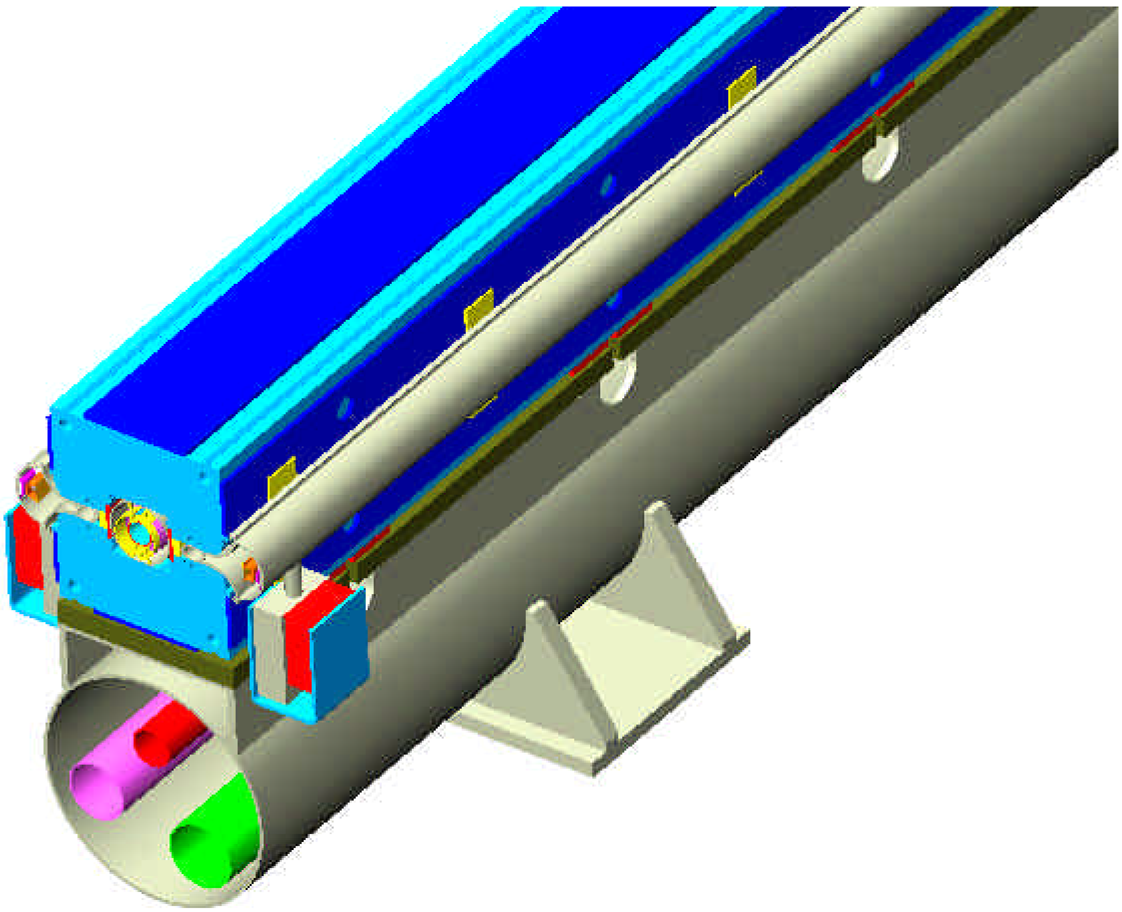

Figure 2.7. The superferric "Transmission-line" gradient magnet used in the arcs for the Stage-1 VLHC.

The magnet and its associated systems are discussed in detail in Chapter 5. The magnet is energized by passing 100 kA through the superconducting cable in the center of the steel yoke, which induces a magnetic field that circulates in the yoke and through the gaps. The magnetic fields in the gaps on either side are in opposite directions for the oppositely directed beams of protons. The current returns in a similar cable in the helium supply/return line in the cryogenic service pipe below the magnet. The separation of the two cables generates a small dipole fringe field in the tunnel. The gaps are narrow to keep the magnet and the excitation current as small as possible. With a two-centimeter gap on either side the magnet will reach 2 T at 90 kA. The small beam pipe creates some stability issues for the beam, and although standard methods seem to be able to keep them within bounds, it is a subject for further study and R&D. Since the steel yoke and the beam pipes of this magnet are warm, the cold mass of this design is very low, so cool-down times and inventory is impressively small. In addition, the electromagnetic force on the conductor is small, permitting a support structure with very low heat leak, hence, low operating power.

Every half-cell, 135 m, the conductor in the center of the magnet is bent down to be close to the return conductor. This is a complication in the cryostat, but creates a field-free region at room-temperature that is used for the various correction magnets: a closed-orbit dipole, a tune quadrupole and a sextupole. Other correctors could be added as needed. All of the correctors are conventional air-cooled iron and copper magnets powered by local DC-to-DC converters. There are also the usual collection of special magnets in the utility straight sections. These comprise Lambertson-style septa for the beam-extraction system, which operate in series with the main excitation bus so they are always at the correct bend strength; injection and extraction kicker magnets, also in the utility straight sections; conventional quadrupoles that carry the FODO lattice across the utility straight sections; and strong, single aperture quadrupoles and bending magnets to focus the beams and bring them into collision at the two interaction regions.

The interaction region quadrupoles are typical of the magnets that will be developed for LHC second-generation IRs. They operate at about 300 T/m gradient and have a larger aperture than the quadrupoles now being built by Fermilab for the LHC, but otherwise look very similar. The improved performance is gained by using Nb_3Sn as the conductor.

Table 2.1. Main parameters and count of magnets in the Stage-1 VLHC.

Magnet Type	**B_{nom} (T)**	**G_{nom} (T/m)**	**L_{mag} (m)**	**Number of elements**	**Notes**
Gradient dipole (arc)	1.97	9.73	65.75	3136	Superferric transmission line
Gradient dipole (Disp. Suppressor)	1.80	16.88	48.81	160	Superferric transmission line
Special dipoles	1.95		25 – 35	52	Separation, recombination, and cross-over
Straight sect quads		70	4.8 – 6.8	464	Water-cooled copper & steel
Low β quadrupoles		300	9.2 – 10.9	16	Nb_3Sn Conductor
Correctors					Air-cooled copper & steel.
Dipole (horiz.)	1.0		0.50	1648	
Dipole (vert.)	1.0		0.50	1648	
Quadrupole		25	0.50	3296	
Sextupole		1750 T/m^2	0.80	3296	

2.5.2 Other Stage-1 Technical Components

2.5.2.1 Cryogenics

The cryogenic system of the Stage-1 collider is distributed over a wide area, but is about the same total refrigeration power as for the Tevatron — 20 MW installed, including 50 % overcapacity. It is a very simple system, with only piping and no pressure vessels in the tunnel. Each refrigeration plant services 38 km of arc magnets. The refrigerator cold box is split, so that the cold stages of the heat exchangers are at tunnel elevation. This reduces the helium gravity head pressure. There are two upstream and two downstream helium loops at each refrigerator. One loop in each direction passes through the transmission line and returns after 10 km. The other loop is bypassed for the first 10 km, and then is switched into the transmission line. This design reduces the size of the transmission line cryostat. There is no liquid nitrogen in the tunnel. The thermal shield for the transmission line and for the cryogenic service pipe is cooled with 40 K helium.

2.5.2.1 Tunnel-Resident Systems

Because of the size of the ring, we have taken special precautions to maximize reliability and minimize maintenance in the long arcs. There is no low-conductivity water system in the arcs, since the corrector magnets are air-cooled. Only repetitive instrumentation and corrector power supplies at each corrector location are required. These electronics are located in radiation-shielded modules buried in cavities (holes in the wall) at each quadrupole location. Average power dissipation is approximately 15 W/m of tunnel. All cables for instrumentation and corrector magnets are pre-assembled on the magnet and factory tested before installation. At alternate half-cells (270 m), cryogenic thermometry and valve controllers are used to regulate the shield flow. Every 10 km there is a walk-in alcove that contains conventional electronics racks and provides network connections, tunnel safety systems, bulk DC power for the instrumentation modules, and cryogenic instrumentation for the cool down valve box.

2.6 Stage-1 Construction and Installation Schedule

The construction of the tunnel is the major cost and schedule issue of the VLHC. It is our goal that the entire construction, installation and commissioning sequence be completed in 10 years. This will require a major logistical effort, since the installation of infrastructure and magnets must be done in one part of the ring while construction is proceeding in another part of the ring. Because the magnets are so long, they must be installed using ramps, not drops. It is presently planned to have installation ramps in two locations, enabling installation in four areas of the tunnel simultaneously. Although infrastructure can be installed in any area in which we have occupancy, magnets can only be installed in areas that are continuous with at least one ramp. To be able to commission the installed components immediately after they are installed, the surface facilities construction must also be coordinated with the tunnel construction.

Because the VLHC is being built at Fermilab, there is the organizational structure to move quickly to plan the construction and installation, and to establish construction activities. Even so, we believe that it will take about one year for the first tunneling to begin at the Fermilab cluster and that the first section in which we can sensibly install will be available at the start of year four. The tunneling and service contracts will follow in sequence, with the last sector completed for installation at the start of year eight. Hence, the complete tunnel construction period is thought to take about six years, and the installation period another six years, overlapped so that the total is ten years, as shown in Figure 2.8. It will take a significant effort to finish the collision halls by the end of year five so that detector installation can start. After magnet installation is completed in a sector, that sector will be commissioned, that is, cooled down and energized, even while installation and perhaps tunneling is continuing in other sectors of the ring.

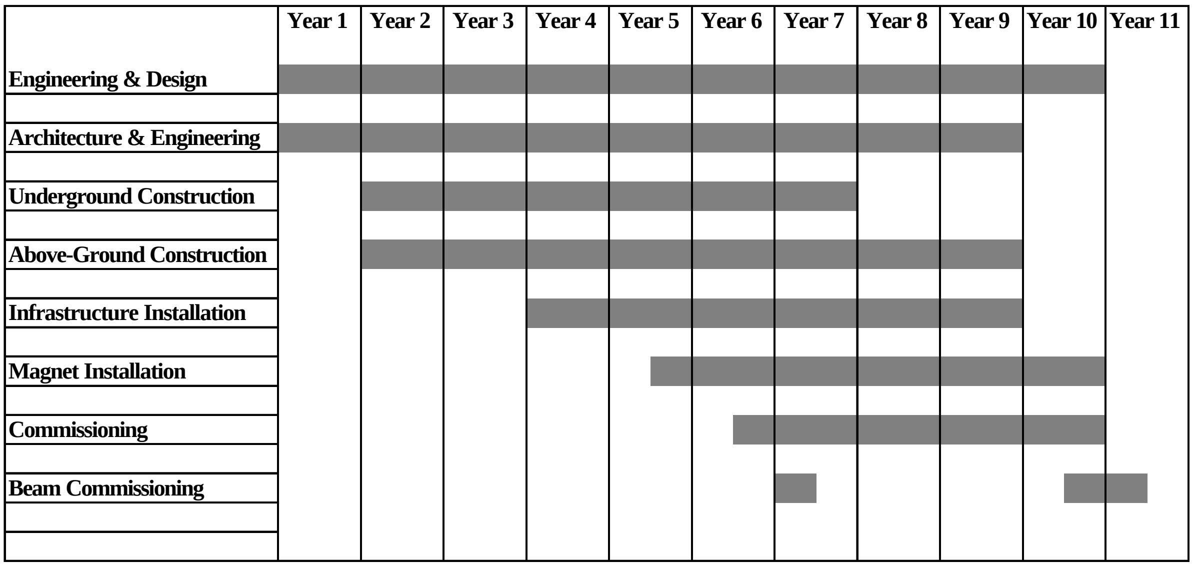

Figure 2.8. An overview of the schedule for construction, installation of infrastructure and magnets, and commissioning.

There are about 600 magnets per sector, so magnet installation will take about 2.5 years per sector at the rate of one magnet per day. Hence, the total installation rate in all sectors will be about four magnets per day. Since our plan has only two magnet-assembly factories, the magnet production will need to start earlier than installation, and a significant amount of magnet storage space will need to be constructed. Other possibilities are to have more magnet-assembly areas or to extend the construction period to 12 years. It is assumed that once a sector adjacent to Fermilab is commissioned, the magnets will be energized and beam may be injected. This will cause some delay in the installation process.

2.7 Stage-1 Operations

The Stage-1 collider can be filled in about one hour from the Tevatron. Because of the cryogenic load of the rapid ramping cycle (50 s), the Tevatron can inject at no more than 900 GeV. The acceleration time to 20 TeV per beam is about 20 minutes, which could be shortened at the expense of more RF. The long luminosity lifetime and long fill time indicate that it will not be a significant advantage to decrease the acceleration time.

Because of the size of the ring, emergency repairs will be time consuming. This will put a premium on reliability, redundancy and regular maintenance. Fully redundant capability is provided for all mission-critical subsystems in the arcs. Power distribution is provided to each module by two independent loop feeders with auto-resetting circuit breakers and remote disconnects. Two independent power supplies are provided for each corrector magnet and control function. Redundant network connections to each module are provided. The critical function of monitoring beam loss is provided by redundant sensors read out from alternate quadrupole modules, so that even the failure of a handful of control modules will not require immediate maintenance. In order to keep such a system reliable, maintenance periods every two weeks will be required to repair the “half-power supplies” that have failed during that period. Because the helium refrigerators have expanders in the tunnel, that part of the cold box is in an alcove far enough from the tunnel to allow access while beam is on, which, in conjunction with generous liquid helium storage, will lead to improved availability.

2.8 Stage-2 Installation

At some point in the operation of the Stage-1 VLHC it will be decided that an energy upgrade is necessary. Production will begin on the high-field dipoles, which although more difficult technically than the superferric magnets of Stage 1 are more conventional in size and appearance. Since Stage 2 will require more than 11,400 double-aperture dipoles, 1700 double-aperture quadrupoles, and about 1700 spool pieces with more than 10,000 correctors of different types, production will require the participation of many industrial companies throughout the world. The magnets can be transported by conventional means and accumulated in industrial storage space so that a large inventory is available at the start of the shutdown. Since the tunnel has a complete infrastructure, magnets can be installed in many locations simultaneously. It is anticipated that the peak installation rate will be about 12 magnets per day, and that the conversion from Stage 1 to Stage 2 will take less than seven years. The major impediment to this fast-track schedule appears to be the ability of what is now a small industrial base to make enough Nb_3Sn wire and cable in the five-year magnet production period. If the magnet production begins earlier and more effort is put into installation, the conversion time could be made shorter.

At the same time as magnet installation is proceeding, the tunnels must be constructed for the Stage-1 bypass, the Stage-1 machine must be rerouted through the bypasses with a few higher-field (about 4 T) magnets, and two new or upgraded detectors must be assembled in the existing collider halls. It seems reasonable that all of these operations could be completed in less than the seven-year conversion time.

2.9 Stage-2 Operation

Since the Stage-2 collider is the same size as the Stage-1 collider, it can be filled in about 30 seconds by transferring multiple Tevatron-length batches already stored in the Stage-1 ring, freight-car style, into the Stage-2 ring. The ramp up to full energy of 87.5 TeV per beam will take about 35 minutes, limited first by the RF accelerating voltage and later by the amount of installed power for the magnet supplies. The energy stored in the magnetic field is returned to the power grid when the magnets are ramped down in preparation for the next cycle. Hence, the minimum time from physics collisions to physics collisions will be about 1.2 hours. We have chosen 10 TeV as the injection energy since that seems completely adequate from the point of view of beam instabilities and dynamic aperture, and because the lower the injection energy, the less costly is the injection equipment, such as kickers and septa.

From an accelerator physics viewpoint the most interesting feature of the Stage-2 machine is that synchrotron radiation will lead to damping of the beam emittance, and hence, a noticeable improvement in luminosity during the store even as the beam is evaporating due to inelastic collisions at the interaction points. This enhancement allows excellent luminosity at reduced beam current, which has the effect of limiting the stored energy in the beam and the compressor power needed to remove the synchrotron radiation power in the cryogenic system. The reduced beam current also reduces the optimum storage time, but at eight hours, that is a small effect on the integrated luminosity. Another interesting consequence of synchrotron radiation is that one can trade off luminosity against operating energy: going up in energy, one does not lose as fast as one might imagine, because the damping becomes more effective. It appears that the Stage-2 VLHC could operate at 200 TeV and 2×10^{34}, as shown in Table 1.2.

2.10 ES&H Issues

During construction, the major environmental issues will be disposal of rock chips from the tunnel and the disturbance to neighborhoods during the construction period. These are non-trivial issues, but they can be handled with appropriate planning, communication and sensitivity. It is clear that a lot of thought will need to be put into organizing the construction effort, particularly since most of the construction will be staged off site in close proximity to private land.

During operation there are a few issues that are similar to those occurring now in all accelerators, but exacerbated by the higher particle energy and total stored beam energy of these machines, and the fact that the VLHC is so large in circumference. Most obvious among these is the so-called “worst-case accident,” which we believe to be the loss of the entire beam at a single point in the arcs of the Stage-2 collider. We have made a preliminary study of this accident, and it appears that it can be handled. It will scar a section of tunnel wall and create a local radiation cleanup problem in the tunnel. It will also irradiate some ground water with tritium and sodium 22, but not to a level that creates a severe environmental or health hazard. The total activation is equivalent to losing the Main Injector beams at a single point for an eight-hour shift. A more plausible accident involves beam damage from an accidental partial firing of the beam extraction kickers. The potential beam damage in this case is confined to several well-defined places which can be protected by special graphite collimators to intercept the beams [1].

One interesting equipment hazard that is unique to the Stage-1 machine is the fringe field caused by the large separation of the drive and return currents in the magnets. When the magnets are energized to full field, there is a region of about 30 cm radius around the magnets and centered approximately at the bottom of the steel yoke, where steel tools can be levitated and accelerated toward the magnets. If they hit the magnets in particular spots they could cause localized but significant damage. This is not a personnel safety issue because no one can be in the tunnel when the magnets are energized, but precautions need to be taken to avoid equipment damage. There will be no measurable magnetic field at the surface for either machine.

2.11 Foci for Future Development

In order to focus the R&D over the next few years, it is first necessary to understand the technical problems that might limit performance or even make the operation of the collider impossible or unsafe; second, to understand the issues connected with construction, fabrication and installation that could delay startup or create unwanted environmental concerns; and third, to enumerate those technical or scientific developments that could, if successful, make the VLHC less costly or lead to improved performance.

2.11.1 Performance Issues for Stage 1

The relatively low energy at injection, the small beam-tube aperture and the large-circumference ring have led to some concern about beam instabilities and tune shifts at injection. Calculations to date and experience on working machines show that a combination of active feedback systems and natural damping mechanisms can handle the instabilities.

During the course of this study we have identified and incorporated two design changes to minimize these issues. Firstly, a bunch coalescing scheme similar to the one used in Tevatron Collider operations has been incorporated to avoid potential single-bunch instability problems at injection. In this scheme, four low intensity 200 MHz bunches are injected, accelerated, and then combined into single high-intensity 53 MHz bunch at collision energy where the instabilities are not an issue.

A second change was made to minimize the tune spread due to time-dependent magnetic image currents in the steel pole tips. This effect is minimized by loading the VLHC ring uniformly around the circumference as described in Chapters 3 and 5. Residual tune spread can be eliminated, if necessary, with a pair of trim quadrupoles operating at audio frequencies.

At this time these appear to be solutions for the most serious potential accelerator physics issue for the Stage-1 VLHC. If further calculations show this to be inadequate, the magnets will have to be redesigned with larger gaps, requiring more steel and a higher drive current. Both of these are cost issues but neither affect the feasibility of the machine. Beam stability will be one of the major R&D efforts for the VLHC.

Other magnet issues are verifying the magnetic field quality for significant quantities of the final magnet design, and systems issues such as thermal load in the transmission line and interconnect design and tests. The issues associated with producing and handling very long magnets need to be simulated and then tested. The insertion quadrupoles have challenges that appear able to be conquered, but the realization needs to be demonstrated. They will require Nb_3Sn technology. A fallback using NbTi would entail approximately a 25% luminosity penalty.

Other issues that might seem problematic have been looked at and although they all need further study, they do not at this time appear to be performance limiting. Among these are ground motion degradation of beam emittance or alignment, the alignment process itself, and the study of potential supercritical flow instabilities in the cryogenic piping of Stage 1.

2.11.2 Construction Issues for Stage 1

The most obvious construction issues for Stage 1 are the long tunnel running under land that is in private or public use, and the massive amount of fabrication and installation. The tunnel construction was mentioned above as an environmental issue, and in Chapter 1 as a public acceptance issue. The planning, tooling and equipment required for handling, assembling, testing, storing and installing and commissioning the long magnets and the subsystems and infrastructure will be a significant challenge. We have created a model of a ten-year construction period with two factories and two installation ramps. It appears that this schedule may be hard to keep, and we may need either more assembly factories and installation ramps, more installation equipment, or a few years longer to complete the job. It may be more cost-effective to have an additional factory, since it also opens up more of the ring to timely installation.

2.11.3 R&D Aimed at Improvements and Cost Reduction for Stage 1

Considering the cost drivers, there are two obvious possibilities for cost savings in the construction of the Stage-1 VLHC: improved and less costly tunneling and underground construction techniques, and cheaper magnets. Investing in R&D in these subjects holds promise for significant reductions in the cost of the VLHC. The major component of tunneling costs is labor, and automation of the process would not only reduce the cost, but make tunneling safer. This R&D would be useful to society at large, in addition to its specific application to the VLHC. There are also many possible tunnel designs. Some may eliminate many of the special underground additions, such as sump pits, egress and access side-rooms, and so forth, all of which add greatly to the cost. These issues need serious engineering that they have not yet received.

Our cost-driver analysis indicates that the superferric magnet is between two and three times less costly per Tesla-meter than conventional superconducting magnets. Automation of the production might make them even more cost effective by reducing assembly and sub-assembly labor. The single most expensive component is the yoke steel, so being able to produce high-quality magnet steel assemblies inexpensively would be a big money saver.

The vacuum system is surprisingly expensive, driven by the costs of the standard ion pumps needed to reduce the partial pressure of non-reactive gasses. Finding a simpler pump design or a getter that will pump methane would drastically reduce the cost of the vacuum system.

2.11.4 Performance and Development Issues for Stage 2

We chose 175 TeV collision energy as the operating energy of the high-energy VLHC, but this study has shown that neither vacuum problems nor local heat-removal issues will arise from synchrotron radiation impinging on the beam-tube liner. The only limitations to operation up to 200 TeV and 2×10^{34} cm^{-2}s^{-1} luminosity appear to be the amount of beam debris power in the IRs and the total compressor power needed to remove the synchrotron radiation power. The first of these will need a dedicated team to study the flow of particles and energy into the detectors and into the magnets close by the interaction point. More sophisticated algorithms to match finer grained and faster detectors close to the IP may be developed and may make a big improvement. The development programs on more radiation-resistant electronics, such as deep sub-micron silicon or diamond-based detectors need to be continued and enhanced. Computer simulations of energy deposition and tests on radiation damage need to be started to understand design and materials issues that may influence the parameters of the interaction insertions and the detectors.

As to the removal of synchrotron radiation power, it appears entirely feasible to place a room-temperature “finger,” or synchrotron radiation mask between magnets that are about 14 meters long that will intercept all or most of the synchrotron radiation, and that will not interfere with the beam or create impedance problems. This can greatly reduce the compressor power, and allow higher luminosity, higher energy, or both. With such a device, collision energies greater than 200 TeV and luminosities greater than 2×10^{34} cm^{-2}s^{-1} are certainly possible.

A possible enhancement of performance could come from using the synchrotron radiation damping to obtain flat beams in collision as is done in all electron colliders. The advantages appear to be in doublet optics in the interaction region, and smaller β_{max} in the quadrupoles. The disadvantages have to do with extremely challenging magnets that would have to operate in the environment of the interaction insertion. This issue and the necessary magnets deserve some study.

References

[1] J. Donald Cossairt et al., “Environment, Safety & Health Considerations for a New Accelerator Facility,” FERMILAB-Conf-01/051-E, April, 2001.